GHGT-14 conference, Melbourne, Australia - Session 6A – 23rd October 2018

Optimization of the post-combustion CO_2 capture process applied to cement plant flue gases: parametric study with different solvents and configurations combined with intercooling

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Partners: HEIDELBERGCEMENT Global Environmental Sustainability, ecra european cement research academy

Outline

- Context of the study
- Simulation principles
- Simulation results
- Conclusions & Perspectives

ECRA Academic Chair

In 2013, ECRA (European Cement Research Academy) and University of Mons signed an important scientific agreement related to the creation of a privileged partnership and the development, within the University, of an academic Chair financed by ECRA.

*The main objective of this academic Chair is to create a centre of scientific expertise in the specific field of "**carbon capture in cement production and its re-use**", and promote research and innovation.*

ECRA Chair prolonged until 2022!

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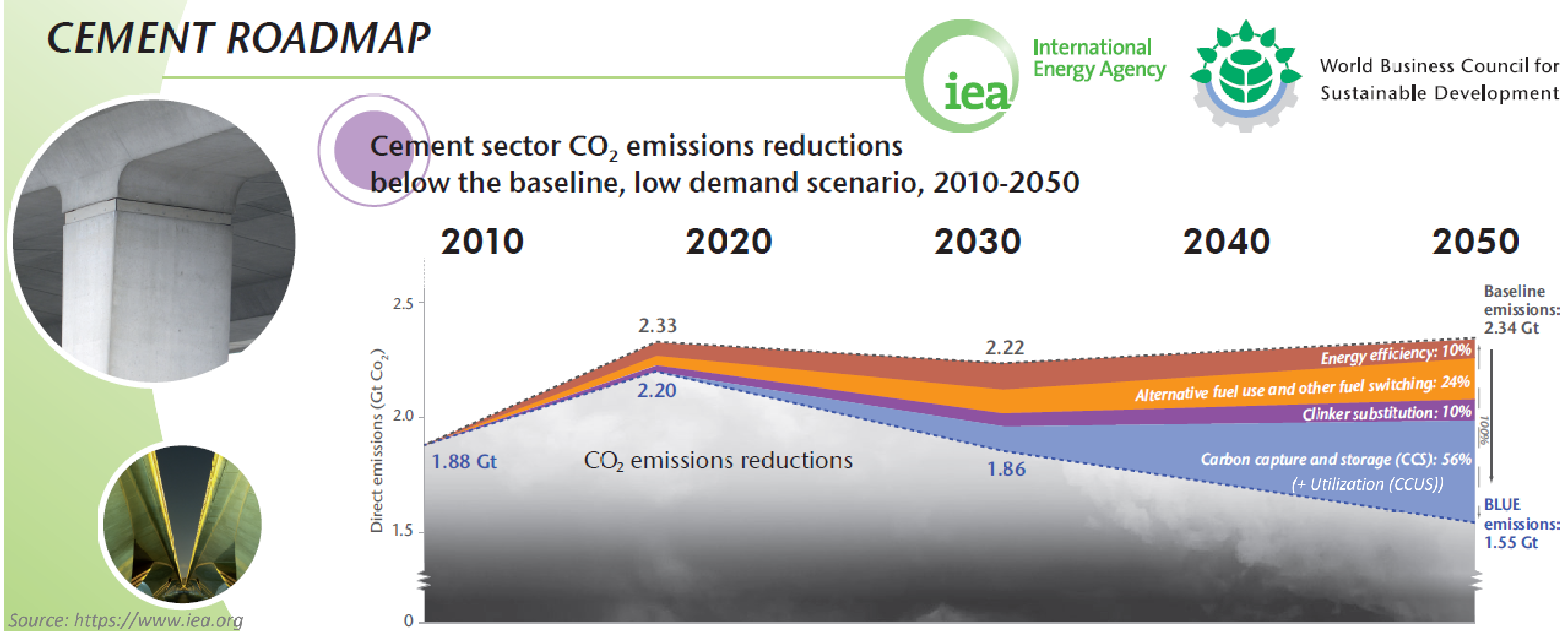
CO_2 emissions – Roadmap and actions

Cement plants ≈ 30% of the industrial CO_2 emissions



CEMENT ROADMAP

International Energy Agency

World Business Council for Sustainable Development

Cement sector CO_2 emissions reductions below the baseline, low demand scenario, 2010-2050

Source: https://www.iea.org

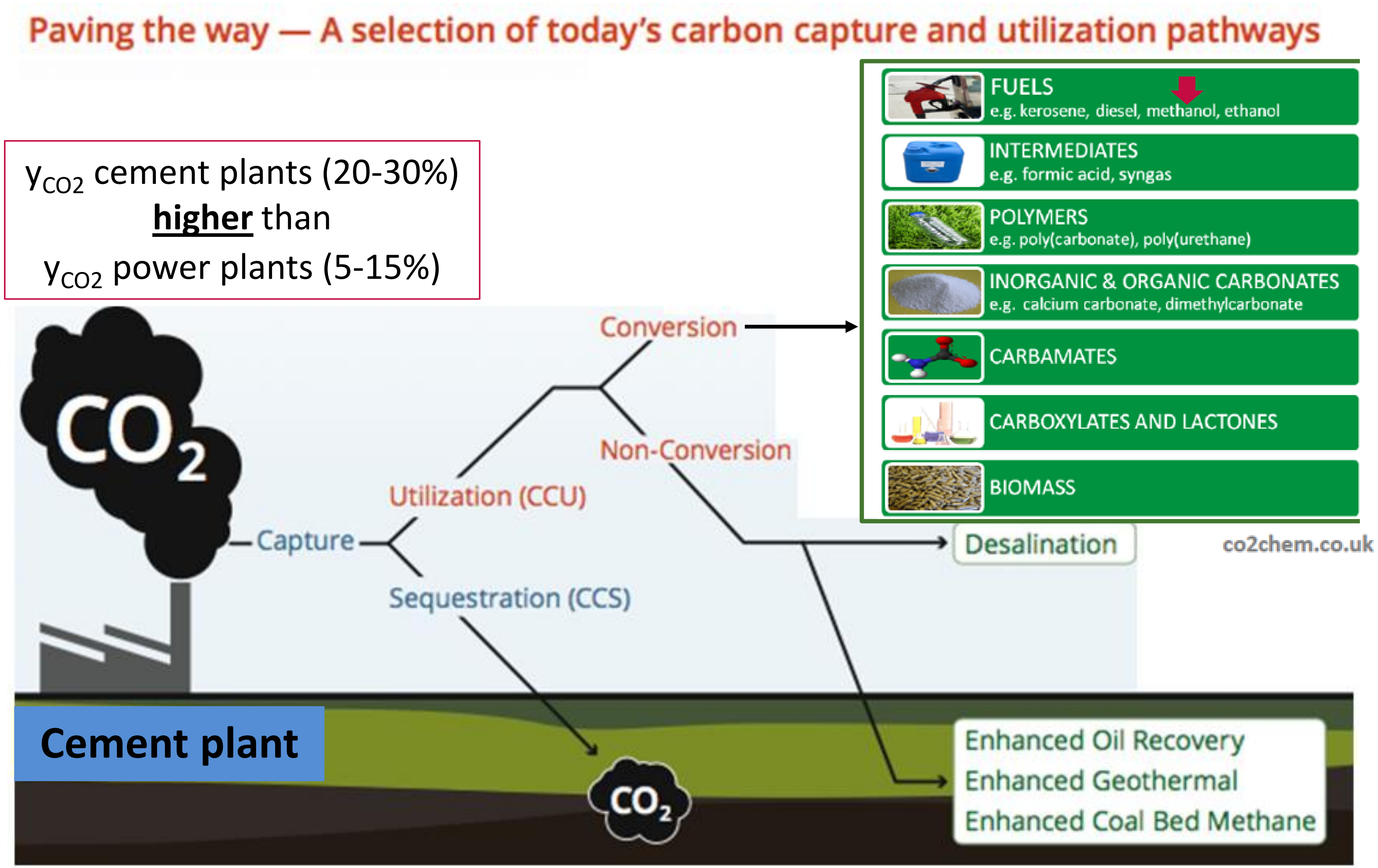
CO_2 emissions reductions

44% thanks to:
- Energy efficiency
- Alternative fuel
- Clinker substitution

56% thanks to Carbon Capture Utilization/Storage (CCUS)

CCSU (Carbon Capture Storage Utilization)

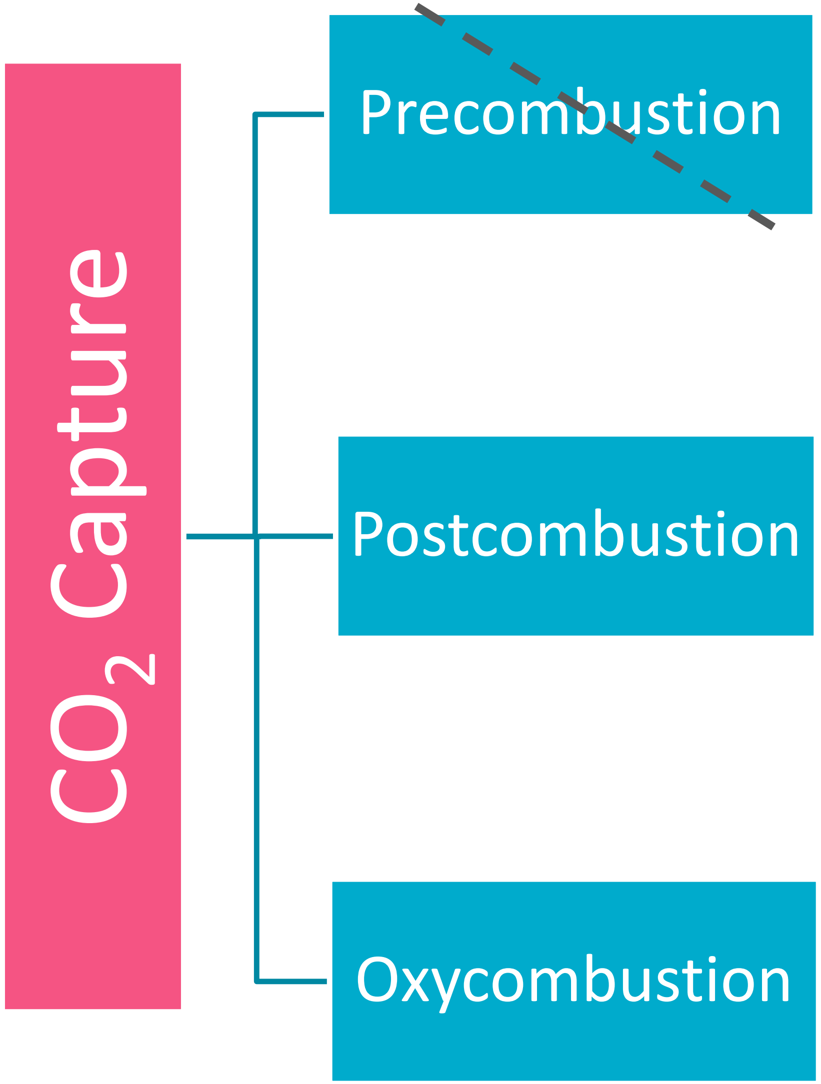
y_{CO2} cement plants (20-30%)
higher than
y_{CO2} power plants (5-15%)



Cement plant

Source: The Pembina Institute with Integrated CO_2 Network (ICO2N)

CO_2 Capture Techniques



CO_2 Capture

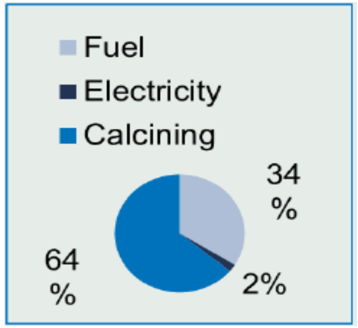
~~Precombustion~~

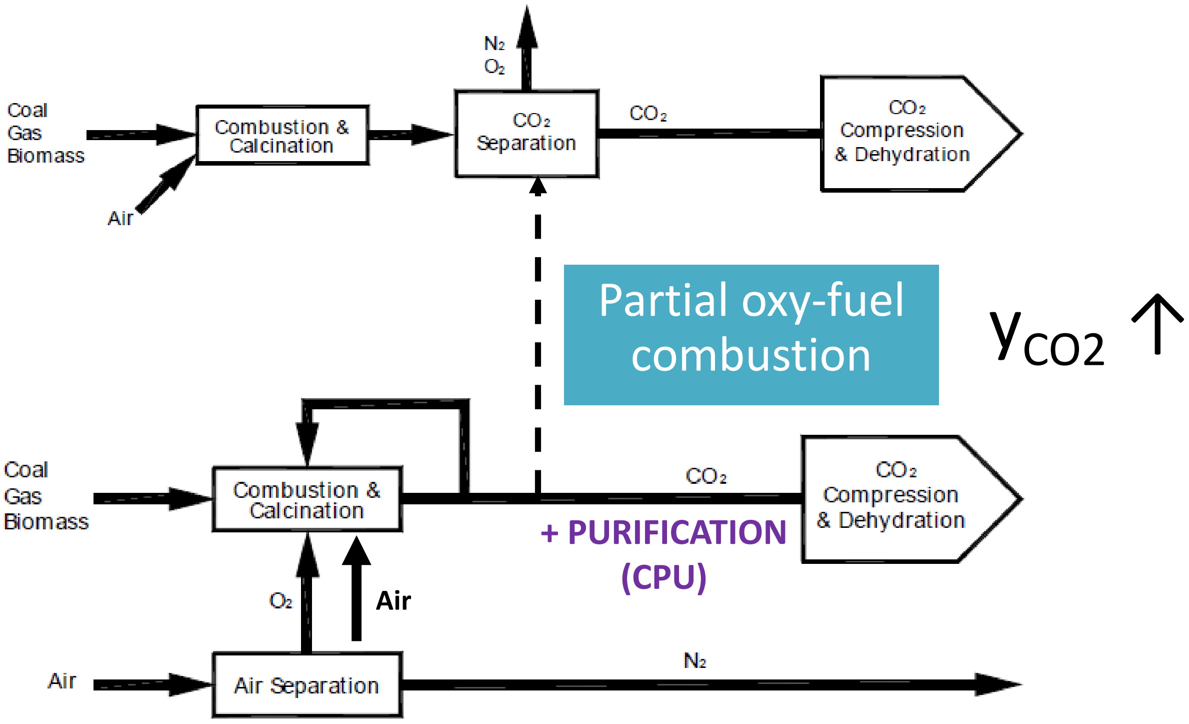
Postcombustion

Oxycombustion

Not interesting for cement industry because most part of the CO_2 is coming from the calcining:

$CaCO_3 + heat \rightarrow CaO + \uparrow \mathbf{CO_2}$





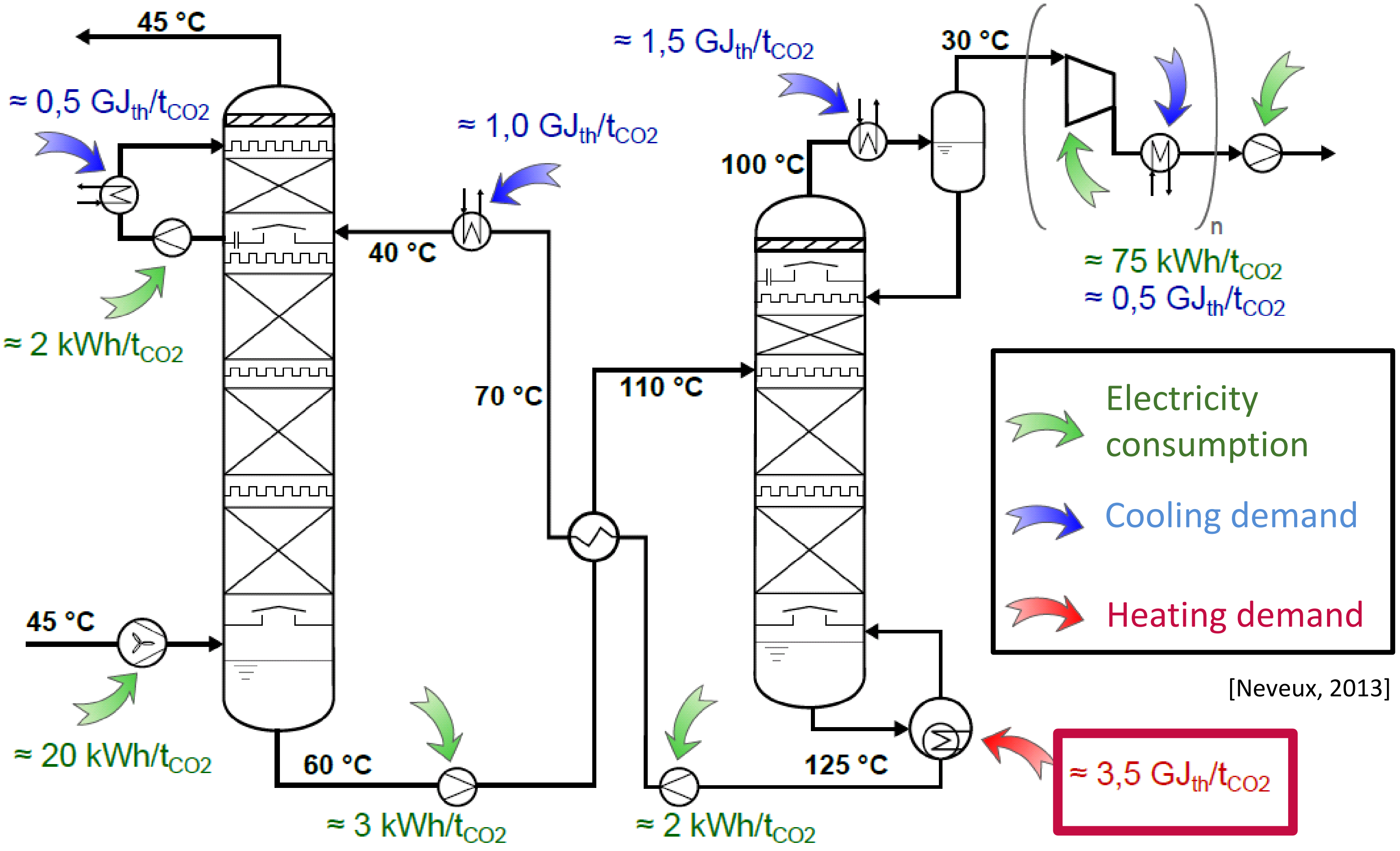
Partial oxy-fuel combustion

y_{CO2} ↑

+ PURIFICATION (CPU)

Absorption-Regeneration Process

Conventional configuration:



[Neveux, 2013]

General principles of the simulations

NORCEM

HEIDELBERGCEMENT Group

Brevik Cement plant

G_{in} = 4000 m³/h
$y_{CO_2,in}$ = 20.4 mol.%

CASTOR/CESAR pilot

$G_{CO_2,regen}$ = 1.5 t CO_2/h
A = 90 mol.%
CO_2 purity = 98 mol.%

≈ 10 x Aker MTU tested at Brevik

Parameters	CASTOR/CESAR
D_{Abs}	1.10 m
$H_{Abs, packing}$	17 m (N_{stage} = 17)
P_{Abs}	1.2 bar
D_{Desorb}	1.10 m
$H_{Desorb, packing}$	10 m (N_{stage} = 10)
P_{Desorb}	2 bar
Packing	Random IMTP 50

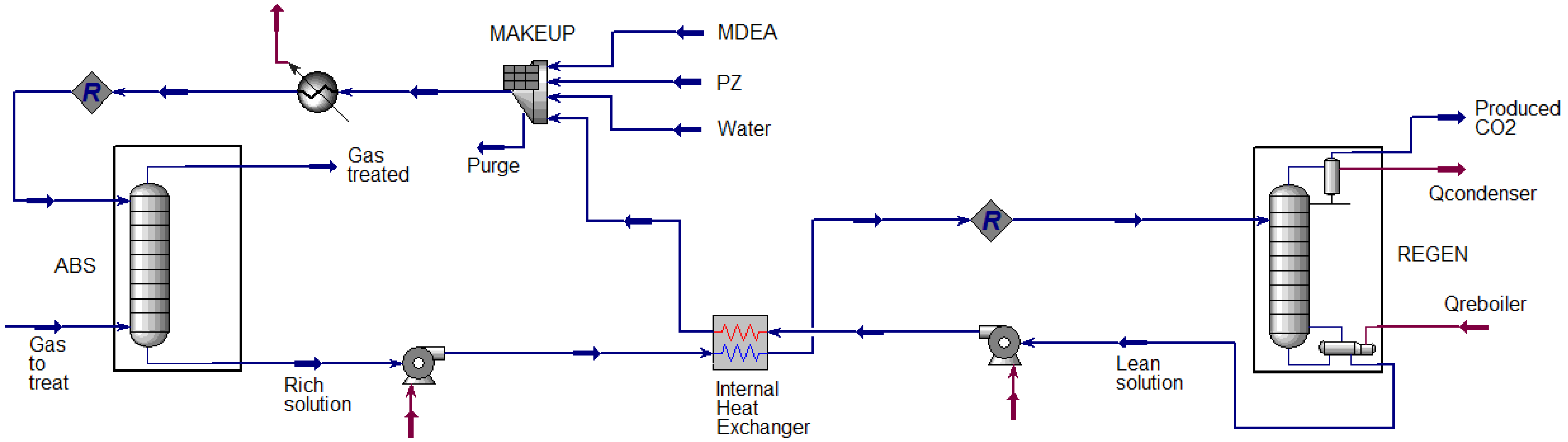
Brevik cement plant = ECRA reference
First European project for testing CO_2 capture from cement industry

Taken as reference
European projects
All data available

Modelling Characteristics:
- Aspen Hysys V9
- Acid gas package
- Thermodynamic models: Peng-Robinson (gas) and e-NRTL (liquid)
- Reactions sets included in the package (validated by literature)

→ For different process configurations & solvents: with/without INTERCOOLING

Base case simulation flow sheet



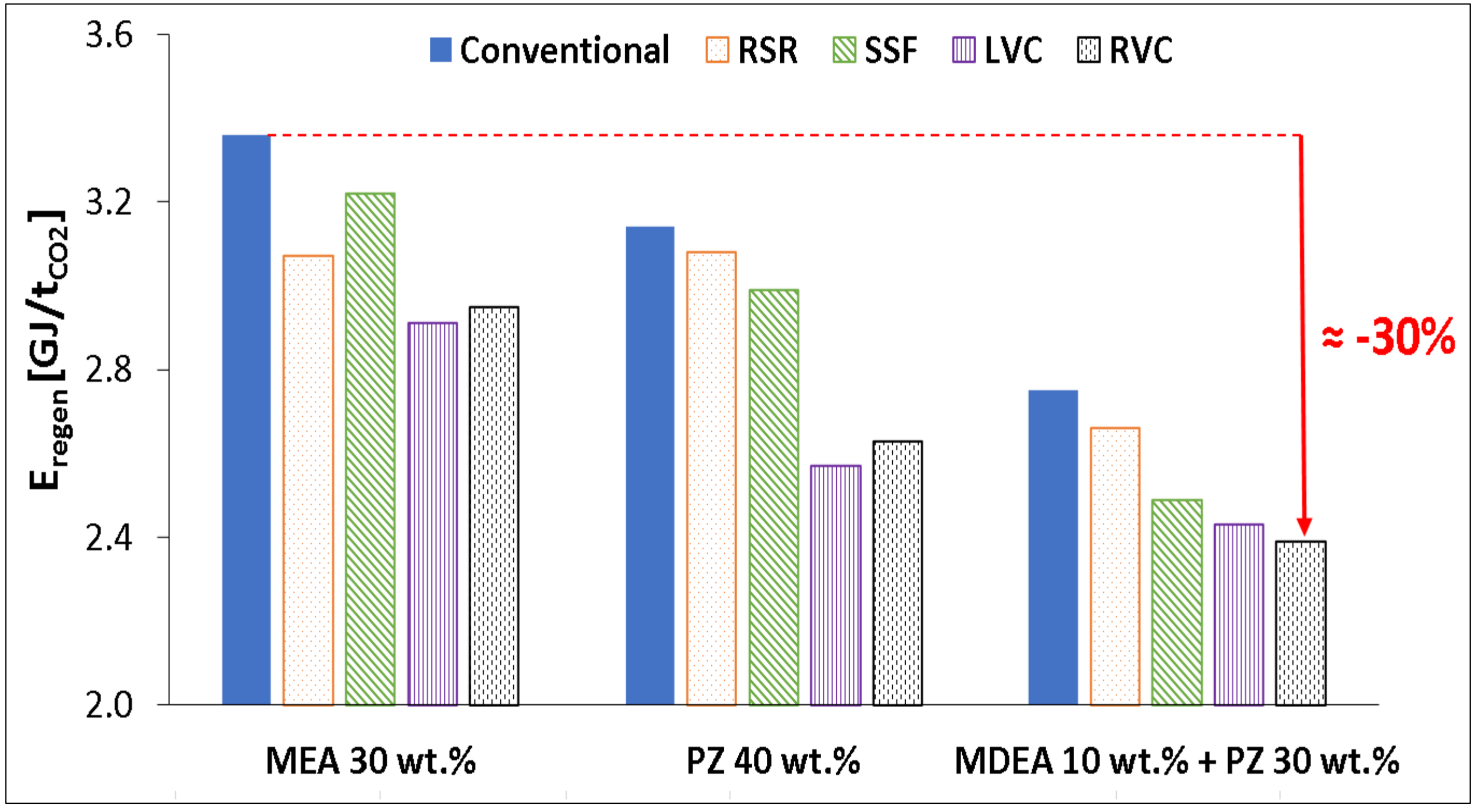
Gas to treat Brevik cement plant	mol fraction
CO_2	0.2040
N_2	0.6470
H_2O	0.0622
O_2	0.0860
CO	1.33E-03
NO_2	1.77E-06
SO_2	1.11E-04
NO	4.74E-04
Ar	/

$$E_{regen}(GJ/tCO_2) = \frac{\Phi_{boiler}}{G_{CO_2,produced}}$$

→ Simulations for three solvents:
- **MEA 30 wt.%**
- **PZ 40 wt.%**
- **MDEA 10 wt.% + PZ 30 wt.%**

Simulation results

Summary of previous simulation results

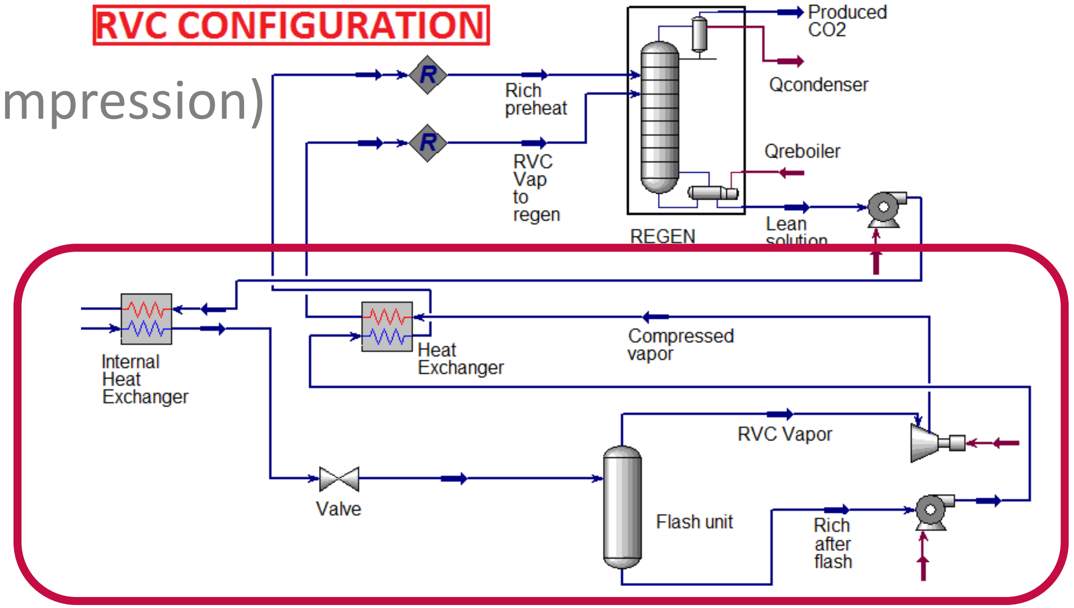


➔Lower E_{regen} with MDEA 10 wt.% + PZ 30 wt.%

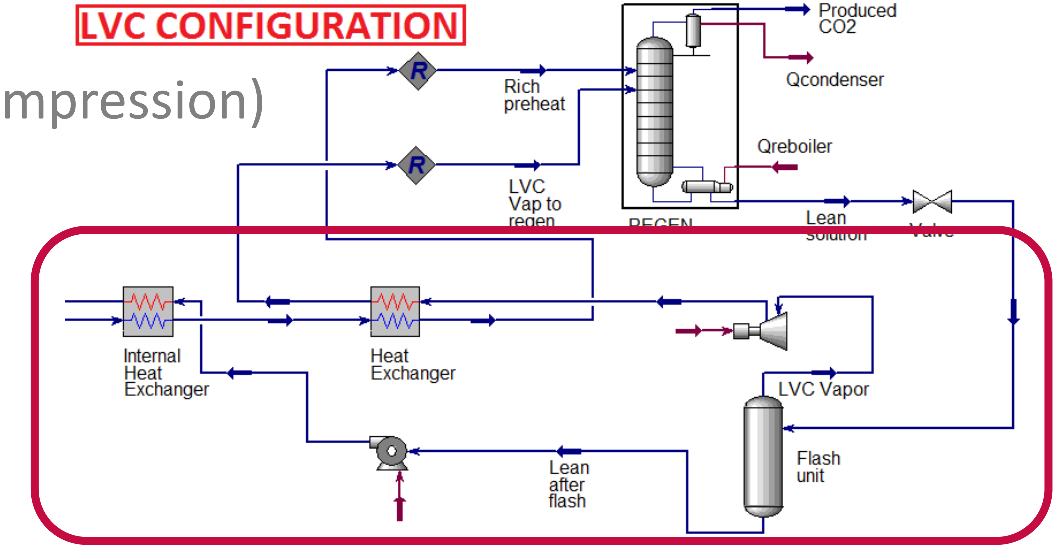
➔**LVC** and **RVC** configurations leading to the minimum of E_{regen} (heat recovery process modifications)

Process configurations

RVC (Rich Vapor Compression)



LVC (Lean Vapor Compression)



Process configurations

CO_2 capture process: advanced flow sheet

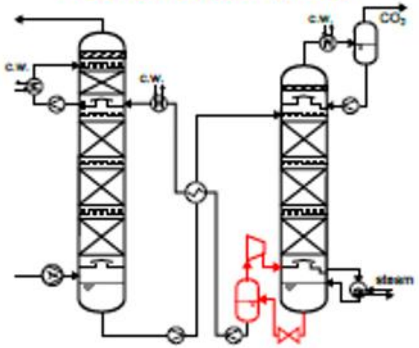
- Other solvents than MEA 30 wt.%:

PZ (piperazine) alone OR activated blend MDEA (methyldiethanolamine) + PZ
$C_{amine,tot}$ = 40 wt.%

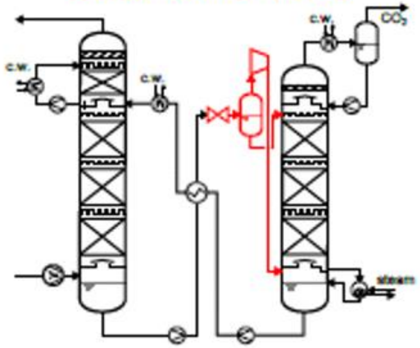
- Alternative process configurations:
  - Temperature level adjustment
  - Better energy integration
  - Promotion of heat recovery

- Water-wash & InterCooling Absorber ICA:
  - Less amine(s) emissions to the atmosphere
  - Optimized absorption temperature
  - ICA leads to higher solvent CO_2 loading

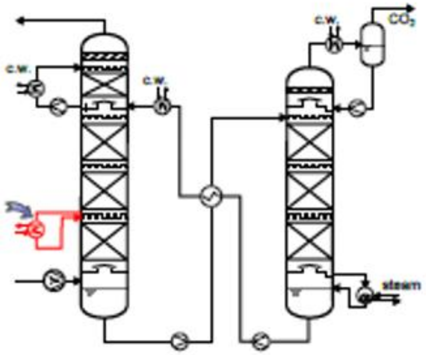
Lean Vapor Compression (LVC)



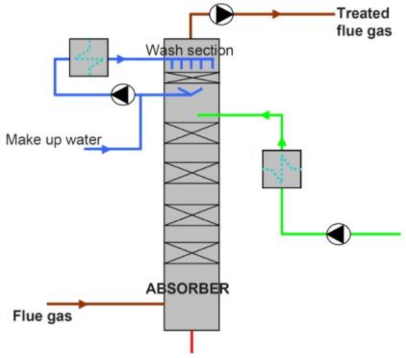
Rich Vapor Compression (RVC)



InterCooled Absorber (ICA)

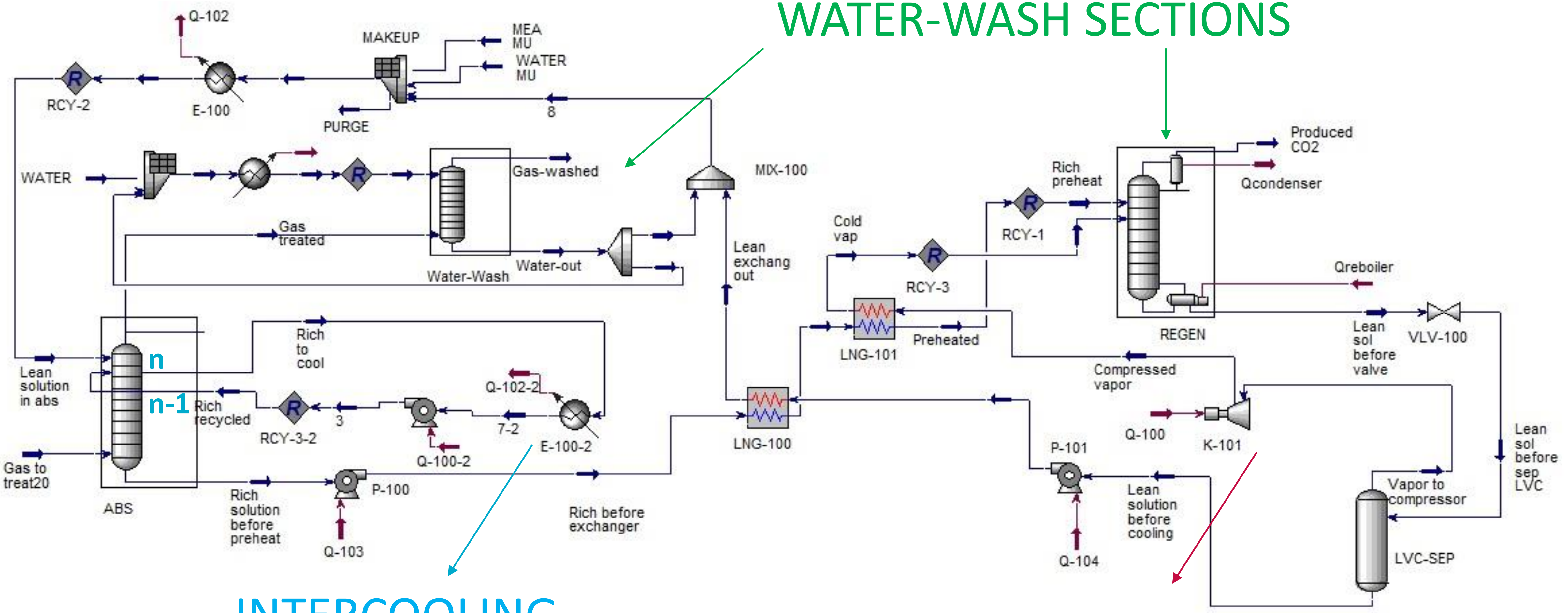


Water-wash (WW)



Process configurations

CO_2 capture process: advanced flow sheet



WATER-WASH SECTIONS

INTERCOOLING

LEAN VAPOR COMPRESSION (LVC)

Simulation results

Indicators used for the results comparison

- Specific solvent regeneration energy: $E_{regen}\,[GJ/t_{CO2}] = \dfrac{\Phi_{boiler}}{G_{CO_2,produced}}$

  Φ_{boiler} [GJ/h] = heat duty provided at the stripper's bottom
  $G_{CO2,produced}$ [t_{CO2}/h] = the rate of CO_2 generated at the stripper's top (outlet of the condenser)

- Total equivalent work:[1] $W_{equ}\,[GJ/t_{CO2}] = E_{regen}\left(1 - \dfrac{T_C + 273.15}{T_H + 273.15}\right)\eta_{turbine} + E_{pumps} + E_{LVC/RVC,compressor}$

  T_C [°C] = steam condensation temperature in the turbine of the power plant providing the electrical energy to the cement plant (≈ 40°C)
  T_H [°C] = steam temperature in the reboiler ≈ T_{regen}+ 10°C
  $\eta_{turbine}$ [%] = turbine efficiency (≈ 75%),
  E_{pumps} and $E_{LVC/RVC,\ compressor}$ [GJ/t_{CO2}] = electrical energies used to run the pumps and the LVC/RVC compressor

- Utilities costs: $C_{utilities}[€/t_{CO2}] = C_{electricity} + C_{cooling\ water} + C_{steam}$

[1] Karimi, M., Hillestad, M., Svendsen, H.F., 2011. Capital costs and energy considerations of different alternative stripper configurations for post combustion CO_2 capture. Chem. Eng. Des. 89, 1229–1236.

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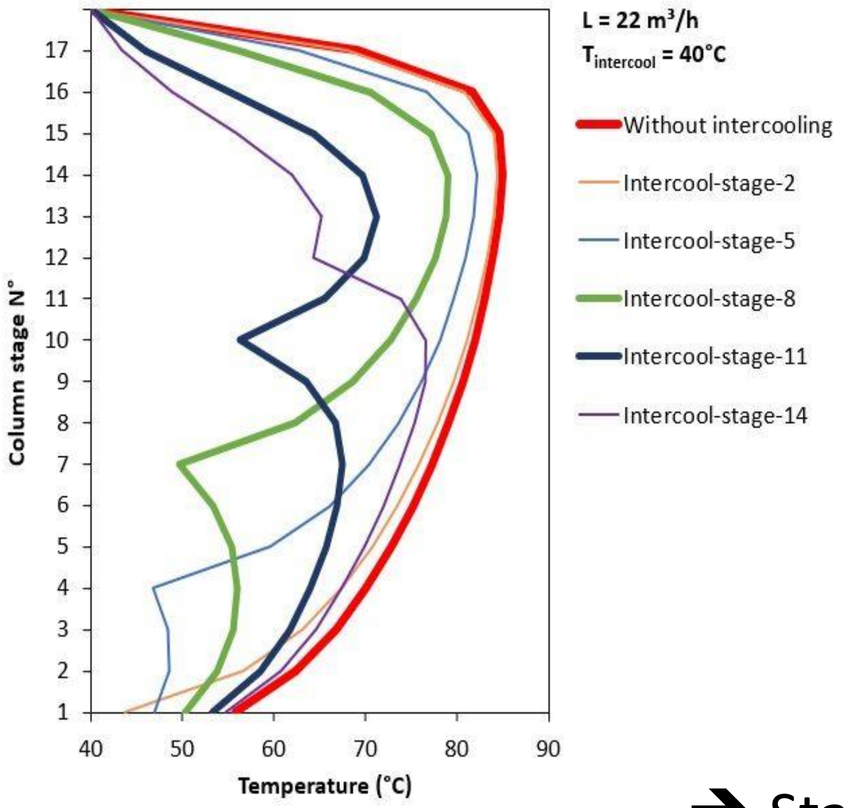
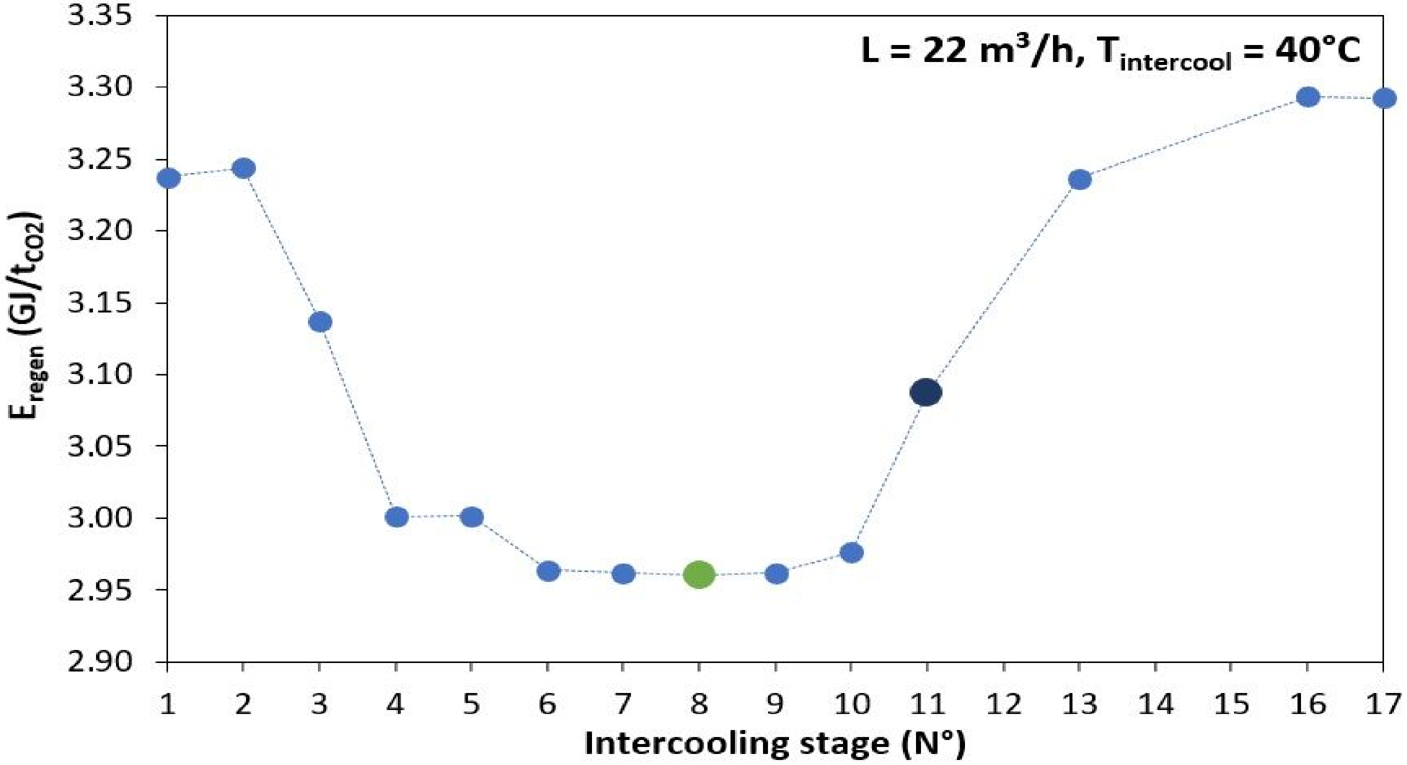
Simulation results

Intercooling parameters optimization

- <u>Intercooling stage (n):</u>

Illustration for MEA 30 wt.% and conventional configuration





➔ Stage leading to lowest temperature ≠ stage lowest E_{regen}

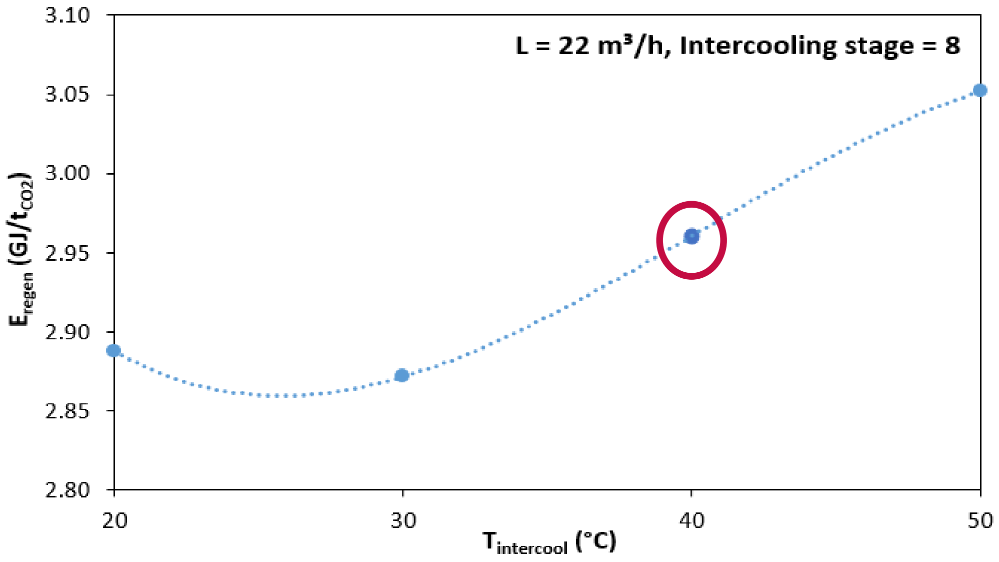
➔ Stage minimizing E_{regen} = 8/17 (6 to 10 = quite similar results)

Simulation results

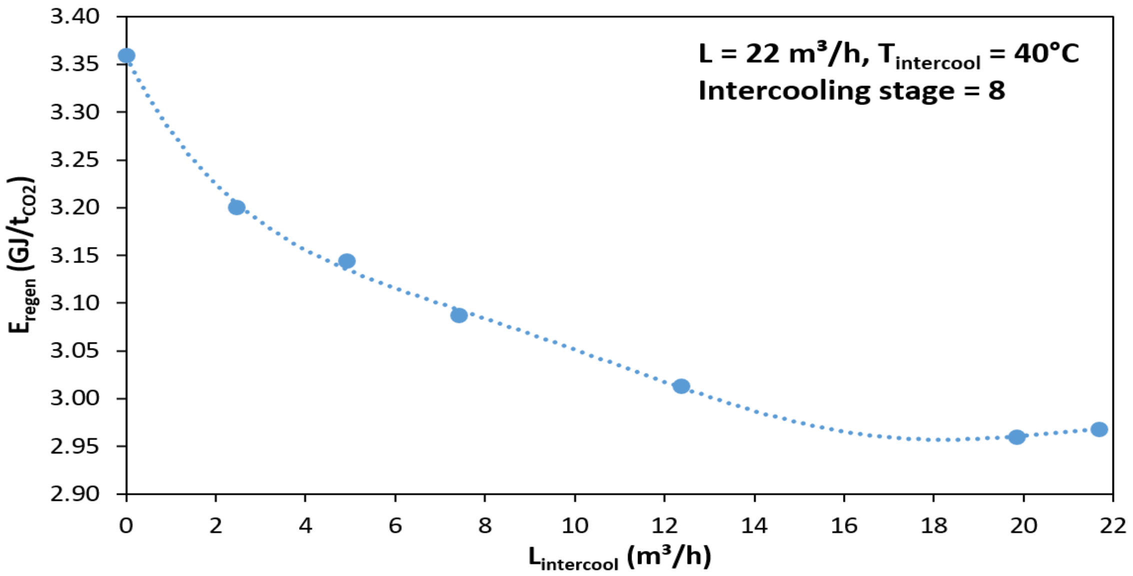
Intercooling parameters optimization

Illustration for MEA 30 wt.% and conventional configuration

- Intercooling temperature:



- Intercooling flow rate:



➔ Cooling temperature fixed at 40°C but interesting if T ↓

➔ If intercooling flow rate ↑, E_{regen} ↓

Simulation results

Water-wash effect for different solvents & configurations

Illustration of the water-wash effect on the amine(s) emissions (mol. fraction) in the absorber outlet gas

$L_{water,WW}$ = 65 kg/h

$T_{water,WW}$ = 40°C

Solvent	Gas without WW	Gas with WW
MEA 30 wt.%	MEA: 107 ppm	MEA: 2 10^{-8} ppm
PZ 40 wt.%	PZ: 114 ppm	PZ: 2 10^{-10} ppm
MDEA 10 wt.% + PZ 30 wt.%	MDEA: 1 ppm PZ: 44 ppm	MDEA: 1 10^{-15} ppm PZ: 5 10^{-13} ppm

≈ traces

Illustration of the water-wash effect on the amine(s) emissions (mol. fraction) in the stripper outlet gas

Solvent	Gas without WW	Gas with WW
MEA 30 wt.%	MEA: 8 10^{-5} ppm	MEA: 1.5 10^{-8} ppm
PZ 40 wt.%	PZ: 2 10^{-7} ppm	PZ: 2 10^{-17} ppm
MDEA 10 wt.% + PZ 30 wt.%	MDEA: 1 10^{-10} ppm PZ: 4 10^{-9} ppm	MDEA: 7 10^{-20} ppm PZ: 5 10^{-18} ppm

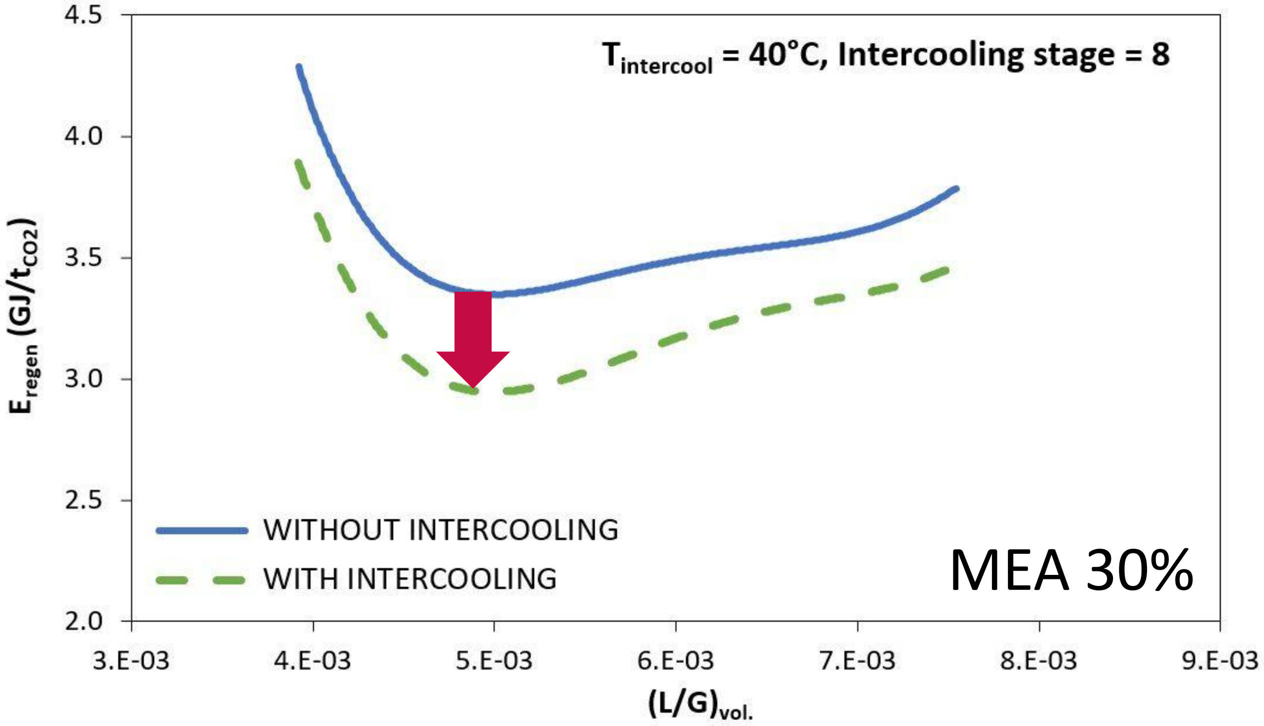
≈ traces

➔ In all cases: WW allows to ↓ amine(s) emissions

Simulation results

Global comparison without/**with** Intercooling

			Conventional configuration			LVC configuration			RVC configuration		
			MEA	PZ	MDEA+PZ	MEA	PZ	MDEA+PZ	MEA	PZ	MDEA+PZ
$(L/G)_{vol,opt}$	**(m³/m³)**	WITHOUT	$5.09\ 10^{-3}$	$3.16\ 10^{-3}$	$3.04\ 10^{-3}$	$5.30\ 10^{-3}$	$6.07\ 10^{-3}$	$3.54\ 10^{-3}$	$7.33\ 10^{-3}$	$6.57\ 10^{-3}$	$3.54\ 10^{-3}$
L_{opt}	**(m³/h)**		22.49	13.97	13.43	23.42	26.83	15.64	32.40	29.03	15.65
$(L/G)_{vol,opt}$	**(m³/m³)**	**WITH**	**$5.02\ 10^{-3}$**	**$4.56\ 10^{-3}$**	**$4.57\ 10^{-3}$**	**$5.48\ 10^{-3}$**	**$4.57\ 10^{-3}$**	**$3.20\ 10^{-3}$**	**$7.31\ 10^{-3}$**	**$4.56\ 10^{-3}$**	**$4.57\ 10^{-3}$**
L_{opt}	**(m³/h)**		**22.21**	**20.15**	**20.20**	**24.23**	**20.20**	**14.14**	**32.29**	**20.15**	**20.20**

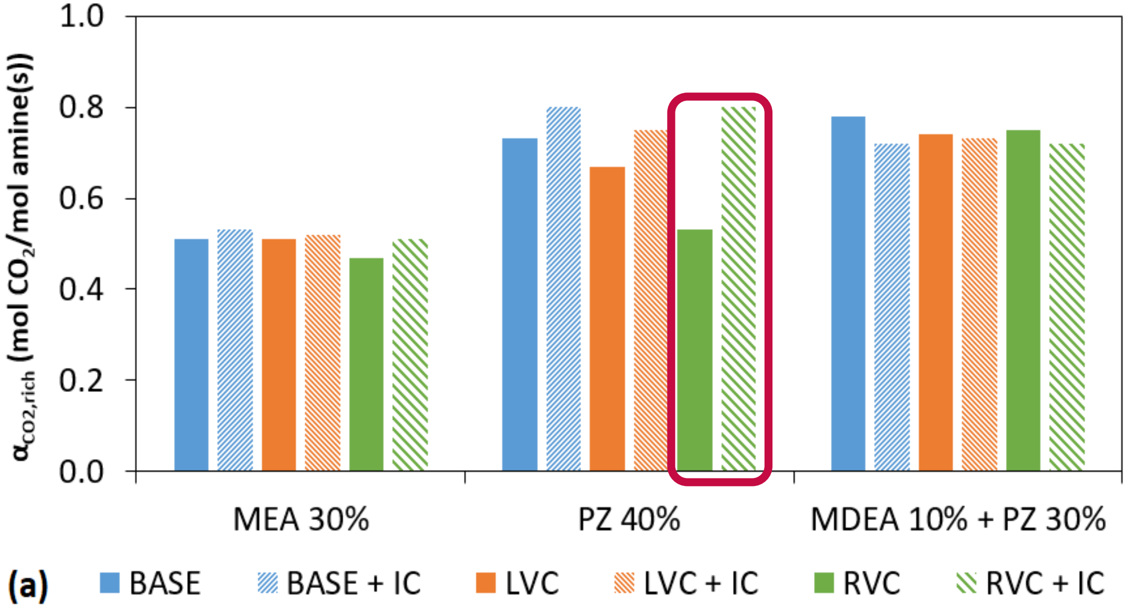


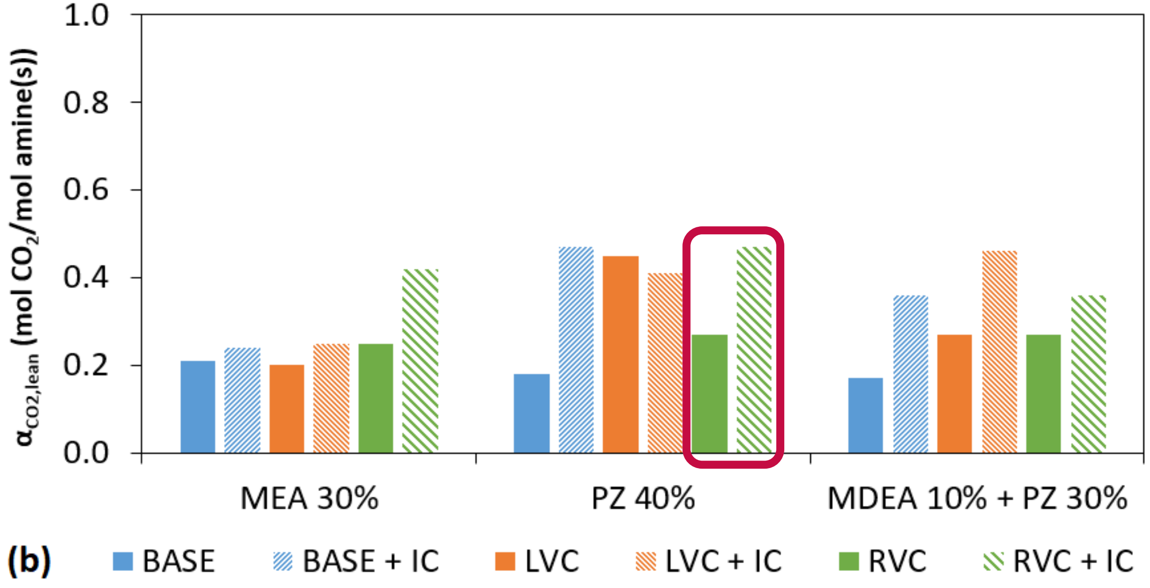
➔ $(L/G)_{vol.}$ ≈ or ≠ with intercooling depending on the solvent & configuration

Simulation results

Global comparison without/**with** Intercooling

		Conventional configuration			LVC configuration			RVC configuration		
		MEA	PZ	MDEA+PZ	MEA	PZ	MDEA+PZ	MEA	PZ	MDEA+PZ
$\alpha_{CO2,rich}$ (mol/mol)	WITHOUT	0.51	0.73	0.78	0.51	0.67	0.74	0.47	0.53	0.75
	WITH	**0.53**	**0.80**	**0.72**	**0.52**	**0.75**	**0.73**	**0.51**	**0.80**	**0.72**
$\alpha_{CO2,lean}$ (mol/mol)	WITHOUT	0.21	0.18	0.17	0.20	0.45	0.27	0.25	0.27	0.27
	WITH	**0.24**	**0.47**	**0.36**	**0.25**	**0.41**	**0.46**	**0.42**	**0.47**	**0.36**





➔ No major effect of intercooling (slight ↑) on α_{CO2} except PZ 40% with RVC

Simulation results

Global comparison without/**with** Intercooling

		Conventional configuration			**LVC configuration**			**RVC configuration**		
		MEA	PZ	MDEA+PZ	MEA	PZ	MDEA+PZ	MEA	PZ	MDEA+PZ
E_{pump} (GJ/t_{CO2})	WITHOUT	$1.61\ 10^{-3}$	$4.99\ 10^{-3}$	$2.33\ 10^{-3}$	$1.68\ 10^{-3}$	$2.36\ 10^{-2}$	$1.37\ 10^{-2}$	$6.42\ 10^{-3}$	$2.56\ 10^{-2}$	$1.37\ 10^{-2}$
	WITH	**$1.59\ 10^{-3}$**	**$8.66\ 10^{-3}$**	**$5.60\ 10^{-3}$**	**$3.99\ 10^{-3}$**	**$1.78\ 10^{-2}$**	**$1.20\ 10^{-2}$**	**$5.26\ 10^{-3}$**	**$1.75\ 10^{-2}$**	**$1.77\ 10^{-2}$**
E_{cooler} (GJ/t_{CO2})	WITHOUT	- 1.51	- 0.60	- 0.44	- 1.04	- 1.19	- 0.30	- 2.36	- 2.04	- 0.24
	WITH	**- 1.12**	**- 0.92**	**- 0.94**	**- 0.87**	**- 0.96**	**- 0.76**	**- 1.19**	**- 0.86**	**- 0.95**
$E_{cooling\ ICA}$ (GJ/t_{CO2})	WITHOUT	-	-	-	-	-	-	-	-	-
	WITH	**- 0.96**	**- 0.85**	**- 0.77**	**- 1.12**	**- 0.62**	**- 0.82**	**- 0.92**	**- 0.86**	**- 0.78**
$E_{LVC/RVC,compressor}$ (GJ/t_{CO2})	WITHOUT	-	-	-	$8.28\ 10^{-2}$	$65\ 10^{-2}$	$37\ 10^{-2}$	$13.6\ 10^{-2}$	$65\ 10^{-2}$	$29\ 10^{-2}$
	WITH	**-**	**-**	**-**	**$8.59\ 10^{-2}$**	**$52.9\ 10^{-2}$**	**$38\ 10^{-2}$**	**$11.1\ 10^{-2}$**	**$41.5\ 10^{-2}$**	**$40.5\ 10^{-2}$**
E_{regen} (GJ/t_{CO2})	WITHOUT	3.36	3.14	2.75	2.91	2.57	2.43	2.95	2.63	2.39
	WITH	**2.96**	**2.89**	**2.67**	**2.74**	**2.50**	**2.31**	**2.82**	**2.26**	**2.19**

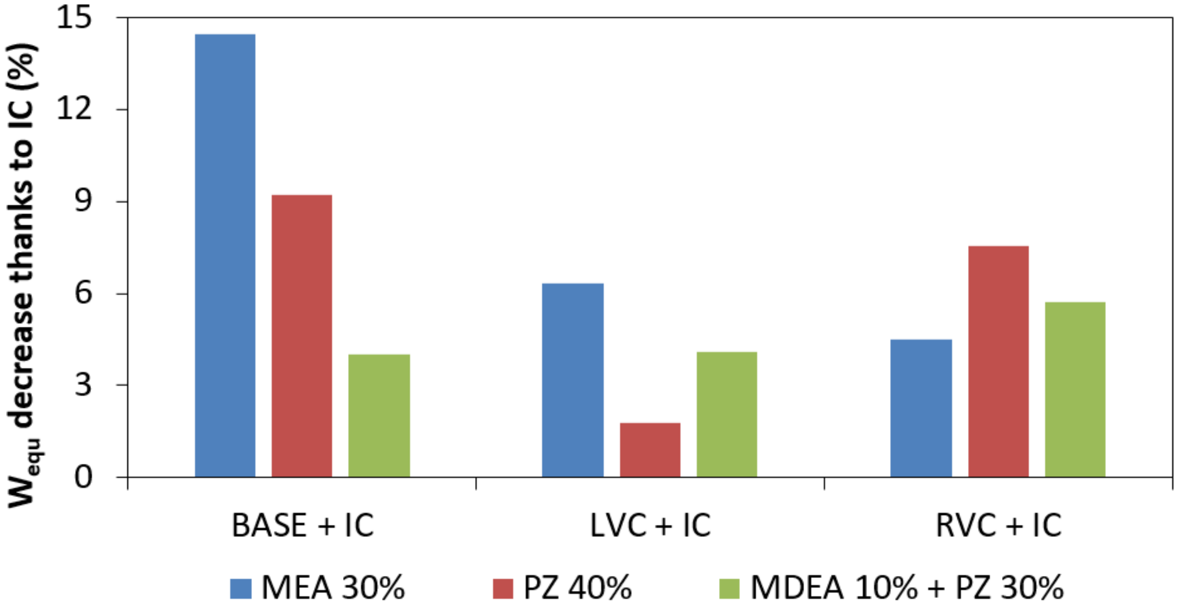
➔ Cooling energy for intercooling ≈ cooling energy for lean solution before absorber

➔ Globally these other energy consumptions clearly << E_{regen}

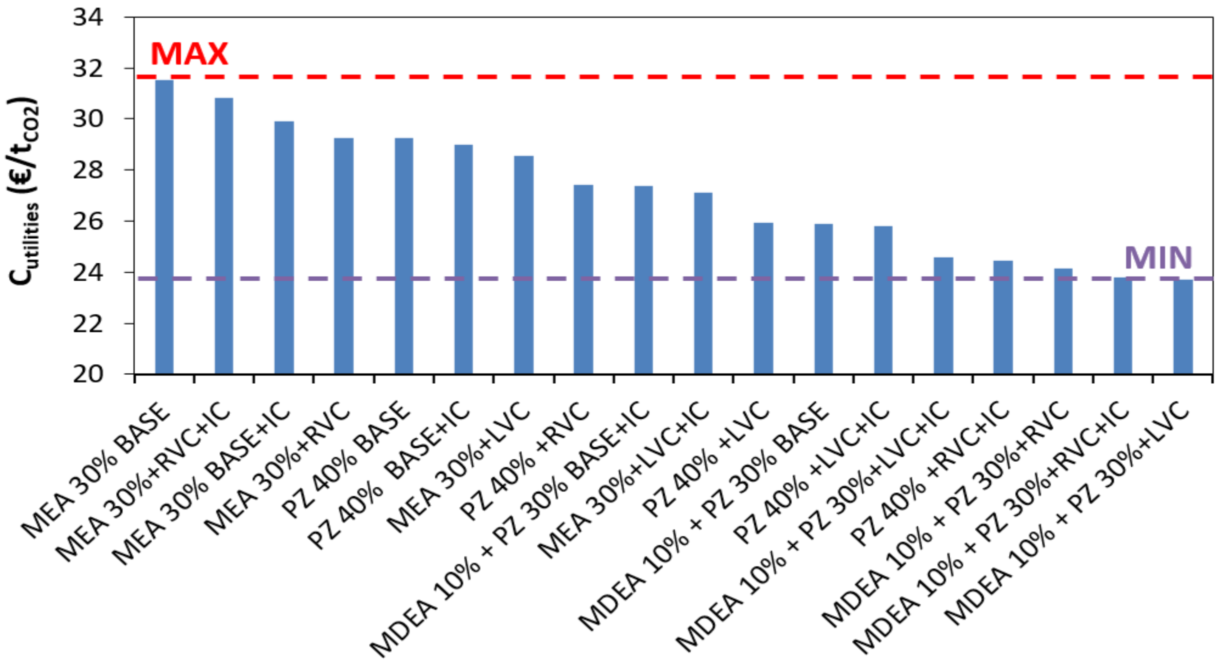
Simulation results

Global comparison without/**with** Intercooling

Equivalent work:



Utilities costs:



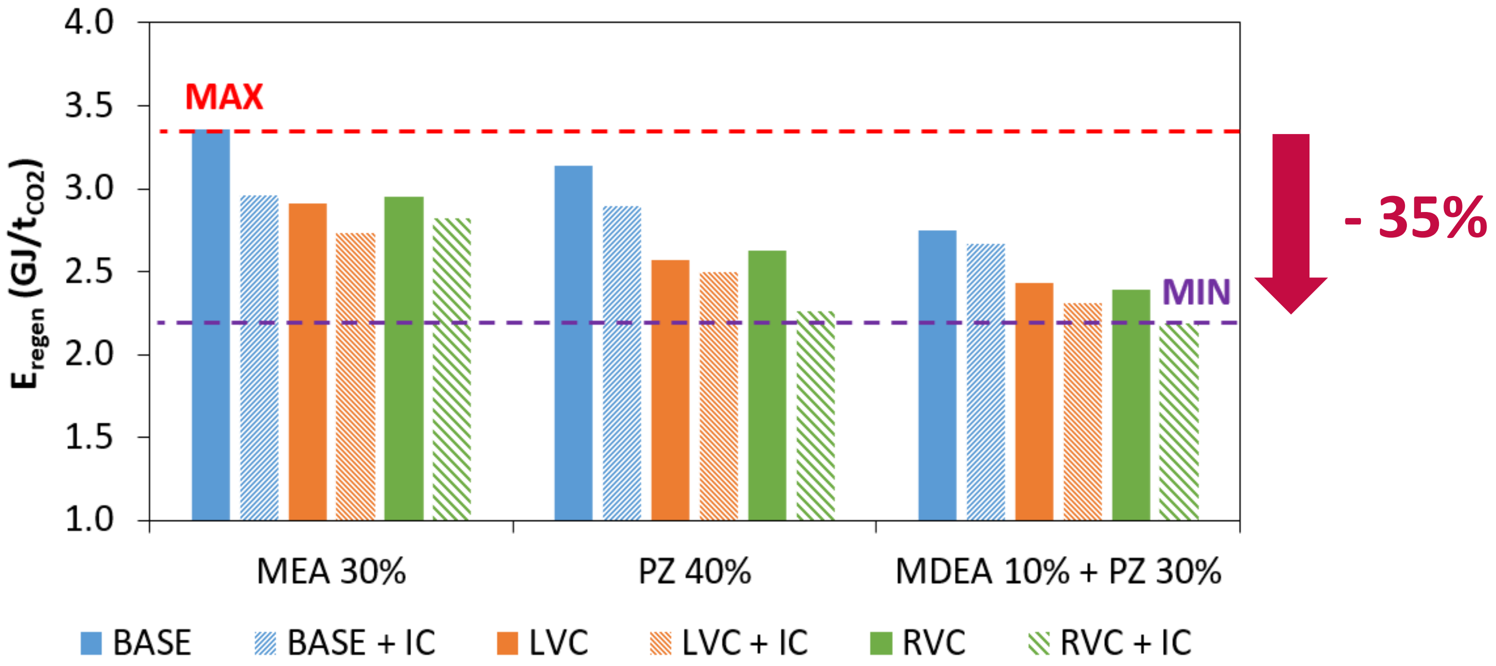
➔ Intercooling leads to a decrease of equivalent work in all cases

➔ Utilities costs can be lower thanks to intercooling depending on the case

Simulation results

Global comparison without/**with** Intercooling

Regeneration energy:



➔ Intercooling leads to supplementary energy savings

➔ Minimum of E_{regen} with **MDEA+PZ + RVC + IC**: **2.19 GJ/t_{CO2}**

→ Globally **35% E_{regen} savings** in comparison with base case

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Conclusions & Perspectives

- Interest of alternative process configurations (LVC/RVC) to ↓ E_{regen}
- Intercooling leads to supplementary energy savings
- PZ-based solutions lead to the lowest E_{regen} values (min = 2.19 GJ/t_{CO2})
- In progress with:
    - Other solvents (e.g. DEA + PZ, demixing solvents)
    - Other cement flue gas (partial oxy-fuel = high p_{CO2})
    - Further analyzes on correlations influence (e.g. interfacial surface area, transfer coefficients, etc.)
    - ...

GHGT-14 conference, Melbourne, Australia - Session 6A – 23rd October 2018

THANKS VERY MUCH FOR YOUR ATTENTION!

QUESTIONS?

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Partners:

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Aker's MTU vs CASTOR/CESAR pilot

Parameters	MTU from Aker tested at Brevik Cement plant	CASTOR/CESAR pilot used for the simulations
Absorber diameter	0.40 m	1.10 m
Absorber packing height	max 18.00 m	max 17.00 m (N_{stage} = 17)
Absorber pressure	-	1.2 bar
Desorber diameter	0.32 m	1.10 m
Desorber packing height	8.00 m	10.00 m (N_{stage} = 10)
Desorber pressure	-	2 bar
Packing type	MellapakPlus	Random packing IMTP 50
Gas flow rate	450 m^3/h	4000 m^3/h
Solvent circulation rate	max 4 m^3/h	max 40 m^3/h
CO_2 capture efficiency	90%	90%
Captured CO_2 flow from Brevik flue gas	≈ 0.15 t_{CO2}/h	≈ 1.5 t_{CO2}/h

≈ x 10

Simulation results

Global comparison without/**with** Intercooling

		Conventional configuration			LVC configuration			RVC configuration		
		MEA	PZ	MDEA+PZ	MEA	PZ	MDEA+PZ	MEA	PZ	MDEA+PZ
E_{pump} (GJ/t_{CO2})	WITHOUT	1.61 10^{-3}	4.99 10^{-3}	2.33 10^{-3}	1.68 10^{-3}	2.36 10^{-2}	1.37 10^{-2}	6.42 10^{-3}	2.56 10^{-2}	1.37 10^{-2}
	WITH	**1.59 10^{-3}**	**8.66 10^{-3}**	**5.60 10^{-3}**	**3.99 10^{-3}**	**1.78 10^{-2}**	**1.20 10^{-2}**	**5.26 10^{-3}**	**1.75 10^{-2}**	**1.77 10^{-2}**
E_{cooler} (GJ/t_{CO2})	WITHOUT	- 1.51	- 0.60	- 0.44	- 1.04	- 1.19	- 0.30	- 2.36	- 2.04	- 0.24
	WITH	**- 1.12**	**- 0.92**	**- 0.94**	**- 0.87**	**- 0.96**	**- 0.76**	**- 1.19**	**- 0.86**	**- 0.95**
$E_{cooling\ ICA}$ (GJ/t_{CO2})	WITHOUT	-	-	-	-	-	-	-	-	-
	WITH	**- 0.96**	**- 0.85**	**- 0.77**	**- 1.12**	**- 0.62**	**- 0.82**	**- 0.92**	**- 0.86**	**- 0.78**
$E_{condenser}$ (GJ/t_{CO2})	WITHOUT	- 1.94	- 0.93	- 0.71	- 0.91	- 0.82	- 0.60	- 1.52	- 0.73	- 0.48
	WITH	**- 1.89**	**- 0.65**	**- 0.63**	**- 0.69**	**- 0.69**	**- 0.62**	**- 0.88**	**- 0.55**	**- 0.51**
$E_{LVC/RVC,compressor}$ (GJ/t_{CO2})	WITHOUT	-	-	-	8.28 10^{-2}	65 10^{-2}	37 10^{-2}	13.6 10^{-2}	65 10^{-2}	29 10^{-2}
	WITH	**-**	**-**	**-**	**8.59 10^{-2}**	**52.9 10^{-2}**	**38 10^{-2}**	**11.1 10^{-2}**	**41.5 10^{-2}**	**40.5 10^{-2}**
E_{regen} (GJ/t_{CO2})	WITHOUT	3.36	3.14	2.75	2.91	2.57	2.43	2.95	2.63	2.39
	WITH	**2.96**	**2.89**	**2.67**	**2.74**	**2.50**	**2.31**	**2.82**	**2.26**	**2.19**
W_{equ} (GJ/t_{CO2})	WITHOUT	0.59	0.71	0.60	0.59	1.24	0.91	0.65	1.26	0.82
	WITH	**0.50**	**0.64**	**0.58**	**0.55**	**1.22**	**0.87**	**0.62**	**1.16**	**0.77**
$C_{utilities}$ (€/t_{CO2})	WITHOUT	31.54	29.25	25.89	28.55	25.94	23.70	29.25	27.42	24.13
	WITH	**29.89**	**29.00**	**27.38**	**27.10**	**25.82**	**24.59**	**30.84**	**24.47**	**23.81**